A review of biodynamic feedthrough mitigation techniques

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Abstract: Biodynamic feedthrough (BDFT) refers to a phenomenon where accelerations cause involuntary limb motions which, when coupled to a control device, can result in unintentional control inputs. Biodynamic feedthrough can occur in many different vehicles and under various conditions, which makes it highly relevant to study its mechanisms. In this paper the possible biodynamic feedthrough mitigation techniques are discussed and evaluated. From these, two solution types are regarded to be the most promising. Measures of the first solution type are already commonly applied and consist of passive measures to restrain and immobilize body parts. The second solution type is the model-based cancellation approach, where use is made of a BDFT model to obtain a canceling signal. The model-based cancellation approach is currently investigated.

Keywords: Biodynamic feedthrough, acceleration feedthrough, manual control, neuromuscular system

1. INTRODUCTION

When a human operator is on-board of a moving a vehicle while performing a manual control task, the vehicle's accelerations can propagate through the body of the human operator, resulting in involuntary limb motions. When coupled to a control device, these limb motions can result in unintentional control inputs, leading to control problems. This phenomenon is called biodynamic feedthrough (BDFT).

Examples of BDFT can be found in many types of vehicles, ranging from electrically-powered wheelchairs (Banerjee et al. (1996)) to heavy hydraulic excavators and bulldozers (Arai et al. (2000)). Also aircraft are vulnerable to BDFT, where it has been identified as the cause of a phenomenon known as roll-ratcheting, a high-frequency roll oscillation that can occur during rolling maneuvers in high-performance aircraft (Höhne (1999); Hess (1998)). Another relevant situation is one where the pilot is exposed to strong vibrations, such as in turbulence (Raney et al. (2001)) or when controlling rotorcraft (McRuer (1994)). Note that BDFT not only plays a role when steering a vehicle but also when executing other manual control tasks while on-board of a moving vehicle. The fact that BDFT can degrade manual control performance in so many ways and under so many different circumstances makes it highly relevant to study its mechanisms.

The goal of this paper is to investigate the solution approaches in biodynamic feedthrough problems. The structure of this paper is as follows: first, in Section 2, a general representation of the BDFT problem is developed. This is used to discover the possible ways to mitigate biodynamic feedthrough. These solution approaches are presented in Section 3 and discussed in Section 4. Finally, the conclusions are provided in Section 5.

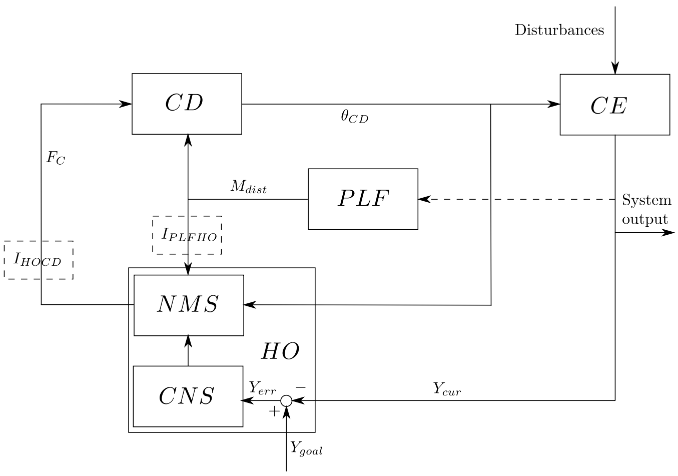

Fig. 1. The general biodynamic feedthrough system

2. THE BIODYNAMIC FEEDTHROUGH SYSTEM

Figure 1 shows a schematic representation of the general biodynamic feedthrough system. In this representation, four main elements can be identified. The human operator (HO) acts as a controller in a manual control task. The HO is controlling the (partial) state of a controlled element (CE) by comparing the current state Y_{cur} with a certain goal state Y_{goal}. The CE can be disturbed by a disturbance signal, for which the HO is requested to compensate. The HO can influence the state of the CE by means of a control device (CD). Control commands are applied by exerting a force, labeled the contact force, F_C, on the CD, resulting in a control input signal, θ_{CD}, that in turn enters the CE. The HO and the CD are connected to a platform (PLF), which is a moving, physical object, typically a vehicle. The acceleration signal coming from the PLF is called the motion disturbance signal M_{dist}. Biodynamic feedthrough occurs when the motion disturbances induce unintentional motions in the limb that is in contact with the CD, thereby leading to unintentional control inputs. In that case, the control input signal θ_{CD} consists of the following contributions:

$$\theta_{CD}(t) = \theta_{CD}^{cog}(t) + \theta_{CD}^{Mdist}(t) + \theta_{CD}^{res}(t), \quad (1)$$

where the superscript *cog* denotes the cognitive element in the control device deflection, i.e, the part that is due to voluntary control actions. The superscript M_{dist} denotes the contribution of the motion disturbance (the biodynamic feedthrough). The remaining part of the control input signal, the part that is not related to a disturbance signal or cognitive control, is here labeled as the residual and denoted by the superscript res. Evidently, for the contact force F_C the same holds:

$$F_C(t) = F_C^{cog}(t) + F_C^{Mdist}(t) + F_C^{res}(t) \quad (2)$$

The feedthrough of PLF accelerations via the body of the HO into the CD is governed by two 'interfaces'. These interfaces describe the dynamics between the human operator and the environment and are indicated in Figure 1 by the dashed boxes, I_{PLFHO} and I_{HOCD}. The interface I_{PLFHO} describes the dynamics of the connection between the PLF and the HO, e.g., seat damping or the effect of seat belts. The dynamics of this interface determine how accelerations enter the body of the operator. The interface I_{HOCD} describes the dynamics of the connection between HO and CD, e.g., grip visco-elasticity or the effect of an arm rest. This interface determines how limb motions result in contact forces F_C. Note that I_{PLFHO} plays a role in the BDFT dynamics only and I_{HOCD} plays a role in both the admittance dynamics as well as the BDFT dynamics.

The human operator model can be split in the central nervous system (CNS), and the neuromuscular system (NMS). The CNS is responsible for all cognitive control commands ($\theta_{CD}^{cog}(t)$) that are neurally communicated to the NMS. The NMS represents the neuromuscular system of the arm connected to the control device and contains body elements such as bones, muscles, etc.

Two types of BDFT systems can be distinguished. In the *closed-loop* BDFT system, the operator's control inputs influence the motions of the PLF (e.g., when steering a vehicle). In the second type, the *open-loop* BDFT system, the human operator has no influence on the motions of the PLF (e.g., when performing a manual control task other than steering while on-board of a vehicle). In this case there exists no connection between the PLF and the CE. To account for these two types of BDFT systems, the connection between PLF and CE is indicated with a dotted line.

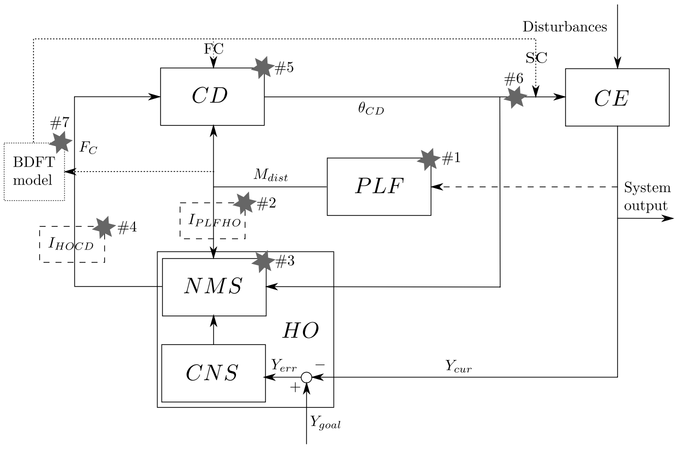

Fig. 2. The solution approaches to the BDFT problem

3. SOLUTION APPROACHES

Several solution approaches exist to reduce the propagation of the platform accelerations, i.e., M_{dist}, through the human body, into the controlled element. The path of propagation of M_{dist} is visualized in Figure 1. In total, seven solution types can be identified, each allowing for one or several solution approaches. The types are indicated with numbered stars in Figure 2. The first three types mitigate the feedthrough of accelerations at one of the elements through which the motion disturbance passes before it enters the CE: the PLF (#1), the NMS (#3), and the CD (#5). The feedthrough of accelerations can also be reduced between these elements, yielding three more solution types: between the PLF and NMS (I_{PLFHO},#2), between NMS and CD (I_{HOCD},#4) and between the CD and CE (#6). Finally, there is the cancellation approach (#7), that uses a model to determine a canceling signal based on the vehicle accelerations. This approach is indicated by dotted lines in Figure 2. It differs from the other approaches as it does not reduce BDFT mechanically at or between elements directly, but in a more electronic fashion by calculating a canceling signal. In the following, each of the seven solution types are discussed.

3.1 Minimizing platform accelerations (#1)

Platform accelerations are the source of biodynamic feedthrough effects, so minimizing these accelerations is arguably the most straightforward and practical way of mitigating biodynamic feedthrough. It simply prevents the accelerations that (could) cause BDFT from occurring in the first place. However, in practice, reducing the PLF acceleration involves sacrificing the system's responsiveness. For some vehicles it may be acceptable to trade responsiveness in return for increased safety (e.g., for electric-powered wheelchairs). However, for the majority of the vehicles responsiveness is of greater concern than the feedthrough of accelerations (e.g., fighter jets).

3.2 PLF-HO interface design (#2)

By carefully designing the interface between the platform and the human operator (I_{PLFHO}), the feedthrough of platform accelerations into the body of the human operator can be reduced. Common examples are measures such as seat damping and seat belts. Seat damping improves ride comfort and mitigates BDFT effects by reducing the propagation of accelerations through the seat. Restraining systems such as seat belts immobilize the trunk and hence reduce the propagation of accelerations into involuntary trunk motion. Although these measures are a simple and cost effective way of reducing the feedthrough of accelerations, they are often not sufficient to completely remove BDFT effects (Raney et al. (2001)).

A more rigorous way of preventing vehicle accelerations from entering the human body is to isolate the HO from the PLF accelerations. A system based on this approach was developed and investigated in Schubert et al. (1970). The Active Vibration Isolation System (AVIS) actively compensates for platform accelerations in the vertical direction, such that the human operator is isolated from the accelerations. In principle, this approach allows for complete removal of BDFT effects, although its implementation comes with many difficulties. In Dimasi et al. (1972), the AVIS was used to test various body isolation configurations consisting of combinations of torso, hand and foot isolation. The results suggested that isolation yields an improvement in ride comfort, as was expected. However, evaluation of tracking performance showed significant improvement only if *all* the elements that the HO interfaces with, i.e., the seat, the displays and the controls, were isolated. The feedthrough of acceleration depends on the relative motion between the HO and these elements, rather than the HO's inertial motion alone.

There are more drawbacks to consider when isolating the HO in an attempt to minimize BDFT. The first is the unavoidable complexity (and thus costs) of the mechanical system that is required to fully compensate for fast and often highly stochastic platform accelerations. Secondly, and more important, platform accelerations also form an important source of *information* on the state of the vehicle, as it provides motion cues. Isolating the human operator from platform accelerations removes these essential cues, degrading the operator's situational awareness and often degrading control performance.

3.3 Neuromuscular adaptation (#3)

Experiments have shown that some settings of the neuromuscular system decrease BDFT, while others increase it (Venrooij et al. (2009)). However, the importance of the variability in HO's neuromuscular dynamics in the occurrence of BDFT is not always recognized. In many common BDFT situations in everyday vehicles, the occupants react, often rather unconsciously, by attaining a NMS setting that minimizes the feedthrough of accelerations. An illustrative example can be found for helicopter pilots, who are trained to hold the control devices loosely (often with only two fingers) while keeping the body relaxed. This control strategy (being 'compliant') reduces BDFT because the coupling between platform dynamics and the control device – formed by the body of the human operator – is made very weak. This approach is analogous to connecting two mechanical systems using a weak spring; if one of the systems moves, only a small portion of this motion is transferred. Advantages of this approach are that it is practical, broadly applicable and does not require adaptations of the vehicle itself. However, the 'compliant' control strategy is often suboptimal in terms of control performance. For fast and accurate (i.e., 'high gain') control a stiffer, tighter grip on the control device would be beneficial (van der Helm et al. (2002)). It can be said that by attaining a BDFT minimizing NMS setting, a part of the available control bandwidth is sacrificed for a reduction in acceleration feedthrough.

3.4 HO-CD interface design (#4)

Also in the design of the interface between the human operator and the control device (I_{HOCD}) there is room for BDFT reducing measures. These measures rely on supporting or immobilizing the limb that is in contact with the control device. A good example of this approach is the commonly used arm rest. Many vehicles, e.g., many aircraft, provide arm rests, mainly to increase comfort and reduce fatigue, but they are also very effective in stabilizing the arm when subjected to motion disturbances. To prevent the propagation of acceleration through the control limb, the limb can also be restrained, just as is often done with the torso by means of seat belts. Application of this approach is, however, very limited as such restraints also limit the *voluntary* actions when the HO wants to manipulate other objects (e.g., press a button).

Just as the restraining approaches discussed in Section 3.2, the measures discussed here are simple and cost effective, but often not sufficient to completely remove BDFT effects (Raney et al. (2001); Sövényi and Gillespie (2007)).

3.5 Control device design (#5)

By reducing the control device responsiveness to some of the frequency content of the control forces, the level of involuntary control input that propagates through the CD and enters the CE can be reduced. An important assumption when using this method is that there exists a clear bandwidth separation between voluntary, cognitive control inputs and involuntary, vibration induced, control inputs. In the following, this assumption is referred to as the 'separation assumption'. For example, in some studies it is assumed that cognitive control activity is limited to 1 Hz and vibration induced control activity only occurs at frequencies above Hz (Velger et al. (1984)). However, other studies have shown that reflexive activity plays an important role in the operator's dynamics, which allows the operator to express dynamics at frequencies also above 1 Hz (e.g., Mugge et al. (2009)). More importantly, several studies measured BDFT at frequencies lower than 1 Hz (Sövényi and Gillespie (2007); Venrooij et al. (2009)). It is therefore questionable whether the separation assumption is valid under all circumstances. It is likely that for the solution approaches that rely on this assumption either the BDFT effects cannot fully be eliminated or that a part of the voluntary control signal is also suppressed. As mentioned in McLeod and Griffin (1989), the optimum dynamical setting for the control device is a compromise between biodynamic feedthrough resistance and controllability.

An alternative approach to reduce BDFT at the control device is to ensure minimal alignment between the manual control axes and the axes of PLF motion. For example, a steering wheel is immune to accelerations in the longitudinal direction, as it has no degree of freedom aligned with this axis. This effectively eliminates the occurrence of biodynamic feedthrough in this directions. This is not the case in, e.g., a side-stick, rendering that type of control device far more susceptible to BDFT. By careful selection the control device and positioning its axes, BDFT can be suppressed. However, in practice, the selection of the control device is based on many factors other than its susceptibility to biodynamic feedthrough. In most cases, the alignment of control and some motion axes cannot be prevented. In fact, aligning the axes of control with the axes of motion is often the most intuitive, and thus preferable, design from a control perspective.

3.6 Signal filtering (#6)

Based on the separation assumption one could conclude that BDFT could be easily mitigated by filtering the control input signal at the BDFT frequencies. Using a static filter to reduce BDFT is referred to as 'input filtering'. For example, Airbus currently uses second order low-pass filters, with a cut-off frequency around 2-3 Hz, in their aircraft fly-by-wire architecture, to remove vibration induced effects from the inputs that enter the control law units. The advantage of this method is that the implementation of such a filter is relatively easy and thus cost effective. Disadvantage is that this approach, again, hinges on the separation assumption.

An alternative filtering approach was proposed in Velger et al. (1984), where an adaptive filtering technique was proposed. In this approach, the filter was adapted based on measurements of the platform accelerations. The approach offers a somewhat 'smarter' alternative to the input filtering, that uses a static filter. However, also here the success of this method relies on the separation assumption.

3.7 Model-based cancellation (#7)

Several studies have investigated BDFT cancellation (Gillespie et al. (1999); Sirouspour and Salcudean (2003); Sövényi and Gillespie (2007)), an approach where an electronically generated canceling signal is injected in the human-vehicle system to cancel feedthrough effects. This approach differs from signal filtering (#6) as it relies on a model to calculate the involuntary motion induced part in the control signal, instead of filtering this part from the signal directly. By adding the cancellation signal to the actual signal, that contains both the voluntary and the involuntary part, BDFT is cancelled. An advantage of this approach is that it does not rely on the separation assumption. A disadvantage of the method is that its success relies largely on the accuracy of the model, making an accurate model a necessity. The cancellation itself can be achieved through two distinct mechanisms (both indicated in Figure 2): force cancellation (FC) and signal cancellation (SC).

Force cancellation This approach is based on mechanically inserting a canceling force or torque at the control device that counters the BDFT part of the force or torque applied by the control limb of the human operator. This method is proposed and tested in several studies: Gillespie et al. (1999); Sövényi and Gillespie (2007). The studies show that this approach is very promising, but that the canceling forces also change the 'feel' of the control device. It is largely unknown whether and how the human operator will *adapt* to these haptic changes and how this adaptation, in turn, will influence the occurrence of biodynamic feedthrough.

Signal cancellation An alternative canceling approach is to subtract the modeled BDFT control input from the total control input, before it enters the controlled element. This method was used in, e.g., Sirouspour and Salcudean (2003) and is referred to here as the signal cancellation (SC) method. It fundamentally differs from the force insertion method, in the sense that it does not cancel the effect of BDFT at the control device, but *after* the control device. Therefore, this approach does not alter the 'feel' of the joystick. However, the disadvantage of this method is that it excludes the human operator from the control loop, by not providing feedback on the activity of the controller. This is not in line with the shared control paradigm. In the shared control paradigm, the controller continually shares the control authority with the human controller, for example by applying its control actions through forces on the control device (Griffiths and Gillespie (2004)).

4. DISCUSSION

Table 1 summarizes the results from the previous paragraph. Currently, many vehicles already offer some of the approaches mentioned. Most used are the passive measures that restrain and support body parts (#2.1, #2.2 and #4.1). Note that these measures by themselves are not sufficient to remove BDFT effects completely. For example, in Raney et al. (2001), BDFT occurred while the pilots were strapped-in tightly in (cushioned) aircraft seats equipped with arm rests. So, even with these measures present, the human is often required to adapt his or her neuromuscular settings to reduce the feedthrough of these accelerations (#3), especially when exposed to high acceleration environments. It was already mentioned that by doing so, a part of the available control bandwidth is sacrificed in return for reduced acceleration feedthrough. The goal of this study is to increase the understanding of BDFT, to obtain novel solution approaches that no longer require this adaptation. Basically, the aim is to develop vehicle-based measures that prevent or cancel BDFT, regardless of the neuromuscular setting of the human operator. In the following, it is discussed which of the vehicle-based approaches are considered most promising.

As we are interested in a general solution to BDFT, we can discard the approaches that cannot be applied in every vehicle in all situations, being: minimize PLF motion (#1), HO-CD restraints (#4.2), and axes design (#5.2). Secondly, let us discard the approach of PLF-HO isolation (#2.3) due on the many practical complications it involves, which limit the applicability of this approach. Then, the approaches that rely on the existence of a frequency separation are discarded, as this assumption is questionable (Sövényi and Gillespie (2007); Venrooij et al. (2009)). The approaches that are to be discarded based on this observation are the CD dynamics approach (#5.1) and the filtering approaches (#6.1, and #6.2).

Two solution types remain as promising general solutions to BDFT. Measures of the first solution type are already commonly applied and consist of passive measures to restrain and immobilize body parts (#2.1, #2.2 and #4.1). The second solution type is the model-based cancellation approach, where use is made of a BDFT model to obtain a canceling signal (#7.1 and #7.2).

Currently, research efforts are devoted to the development of such a model-based cancellation controller. Which of the two model-based approaches, force cancellation or signal cancellation, yields the best results is still to be investigated. The force cancellation method has the major advantage that it 'informs' the HO of its actions it provides (which is in agreement with the shared control paradigm), but it is unknown whether and how the HO adapts to the haptic support offered by the stick, which is perceived as a change in 'feel' of the stick. For the signal cancellation technique the 'feel' of the control device remains unchanged, but now the HO receives no feedback on the controller's actions.

What both methods have in common is that they are based on a BDFT model. Successful cancellation relies heavily on the accuracy of this model and the development of such a model is a challenging task. However, once such a model is obtained, it will lead to an increased understanding of BDFT, which can be regarded as an additional advantage of the model-based solution approach. Some of the issues that are of importance for the success of this method are: model over-parameterization, parameter validation, and the development of fast online identification techniques. These issues are currently investigated.

5. CONCLUSIONS

Using a general BDFT system, the available BDFT mitigation techniques were discovered. In total, seven different solution types, each providing one or more solution approaches, are identified and discussed in this paper. After discarding the solution types that do not meet requirements on general applicability and allowable complexity or rely on the questionable separation assumption, two solution types remain that are deemed most promising. Measures of the first solution type are already commonly applied and consist of passive measures to restrain and immobilize body parts (e.g., seat belts and arm rests). Studies have shown that these are not sufficient to remove BDFT completely. The second solution type is the model-based cancellation approach, where use is made of a BDFT model to obtain a canceling signal.

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Table 1. Summary of biodynamic feedthrough solution approaches

ID	§	Name	Act./ Pass.	Principle	Example	Major advantage	Major disadvantage
#1	§3.1	Minimizing platform accelerations	A	Limit M_{dist} and prevent BDFT	Acceleration limiter wheelchair	A direct way of BDFT prevention	Sacrifice system's responsiveness
#2	§3.2	PLF-HO design					
#2.1	§3.2	damping	P	Reduce propagation of M_{dist}	Seat cushioning	Low-cost simple solution	Not sufficient
#2.2	§3.2	restraints	P	Immobilize body parts	Seat belts	Low-cost simple solution	Not sufficient
#2.3	§3.2	isolation	P	Isolate HO from PLF	Dimasi et al. (1972)	Complete BDFT removal possible	Complex, expensive system required
#3	§3.3	Neuromuscular adaptation	A	Create weak coupling PLF-CD	Helicopter training	Practical, no adaptations to vehicle required	Sacrifice some control bandwidth
#4	§3.4	HO-CD design					
#4.1	§3.4	support	P	Reduce involuntary limb motion	Arm rest	Low-cost simple solution	Not sufficient
#4.2	§3.4	restraints	P	Immobilize body parts	-	Low-cost simple solution	Limitation of voluntary motions
#5	§3.5	CD design					
#5.1	§3.5	CD dynamics	P	Make CD less sensitive to BDFT	-	Simple solution	Relies on separation assumption
#5.2	§3.5	axes design	P	Do not align axes of control with axes of acceleration	Steering wheel	Immunity to BDFT in certain directions	Not always possible or practical
#6	§3.6	Signal filtering					
#6.1	§3.6	input filtering	A	Filter θ_{CD} with static filter	Low-pass filter Airbus aircraft	Simple solution	Relies on separation assumption
#6.2	§3.6	adaptive filtering	A	Filter θ_{CD} with adaptive filter	Velger et al. (1988)	'Smarter' than input filtering	Relies on separation assumption
#7	§3.7	Model-based cancellation					
#7.1	§3.7	force cancellation	A	Insert opposing force in CD	Sövényi and Gillespie (2007)	Operator in loop (shared control)	Varying CD dynamics (changing 'feel')
#7.2	§3.7	signal cancellation	A	Insert opposing signal in θ_{CD}	Sirouspour and Salcudean (2003)	Constant CD dynamics	Operator excluded (no shared control)